

Earthquake

Highlights

- *Seattle area earthquakes fall into three categories: shallow quakes occurring in the North American plate, deep quakes occurring in the San Juan de Fuca plate, and subduction zone quakes that occur in both.*
- *Future shallow earthquakes could occur along the Seattle Fault which runs east-west through the middle of the city or along newly discovered faults running north-south through Puget Sound. A Seattle Fault quake could be as high as 7.5 to 8.0Mm, but 6.0Mm is more probable.*
- *A subduction zone quake would be centered off the Washington coast and could reach 9.0Mm+.*
- *Deep quakes are the most common large earthquake in the Puget Sound region. Quakes larger than 6.0Mm have occurred in 1909, 1939, 1946, 1949, and 1965.*
- *The Duwamish Valley, Interbay, and Rainier Valley are vulnerable to ground failure and shaking because of the liquefiable soils in them.*
- *Seattle has at minimum 500 unreinforced masonry buildings, a building type considered highly vulnerable to earthquakes. Most are in older parts of the city such as Pioneer Square, Columbia City, and Ballard.*
- *The city is heavily dependent on its bridges. Damage to them would impair emergency services and the economy. Most are being seismically upgraded.*
- *Property damage for quakes in 1949 and 1965 amounted to \$200 million in 1984 dollars. Given the area's growth over the past 33 years, damage today is more likely to be in the billions.*
- *In a large event, secondary impacts such as landslides, fires, and hazardous materials releases could produce as large an impact as the earthquake itself.*

General

Earthquakes are caused when the strain accumulating in rock as a result of the movement of large parts of the earth's crust called plates becomes greater than the strength of the rock or the pressure keeping a fault from slipping. In the Pacific Northwest, the relatively small San Juan de Fuca plate, located off the Washington coast, is sliding under the North American plate. Figure 1 shows how this process works.

Plate movement is primarily driven by very slow moving convection currents in a hot, dense, plastic rock layer of the Earth called the Mantle. Just as hot air rises and cool air sinks, hot mantle material rises cooling as it nears the surface. The cooler material then begins to slowly sink down creating a convection cell.

This process is pushing plates together in the Pacific Northwest. When plates collide, the thinner, denser ocean plate is usually forced under the thicker, lighter rock of the continent. This subduction process usually occurs in a jerky manner. Friction and pressure along the interface of the plates prevents the ocean plate from moving under the continent, locking them together for decades or centuries. When the strain is too great, they slip suddenly causing a subduction zone earthquake.

Pacific Northwest quakes are of three types: shallow,

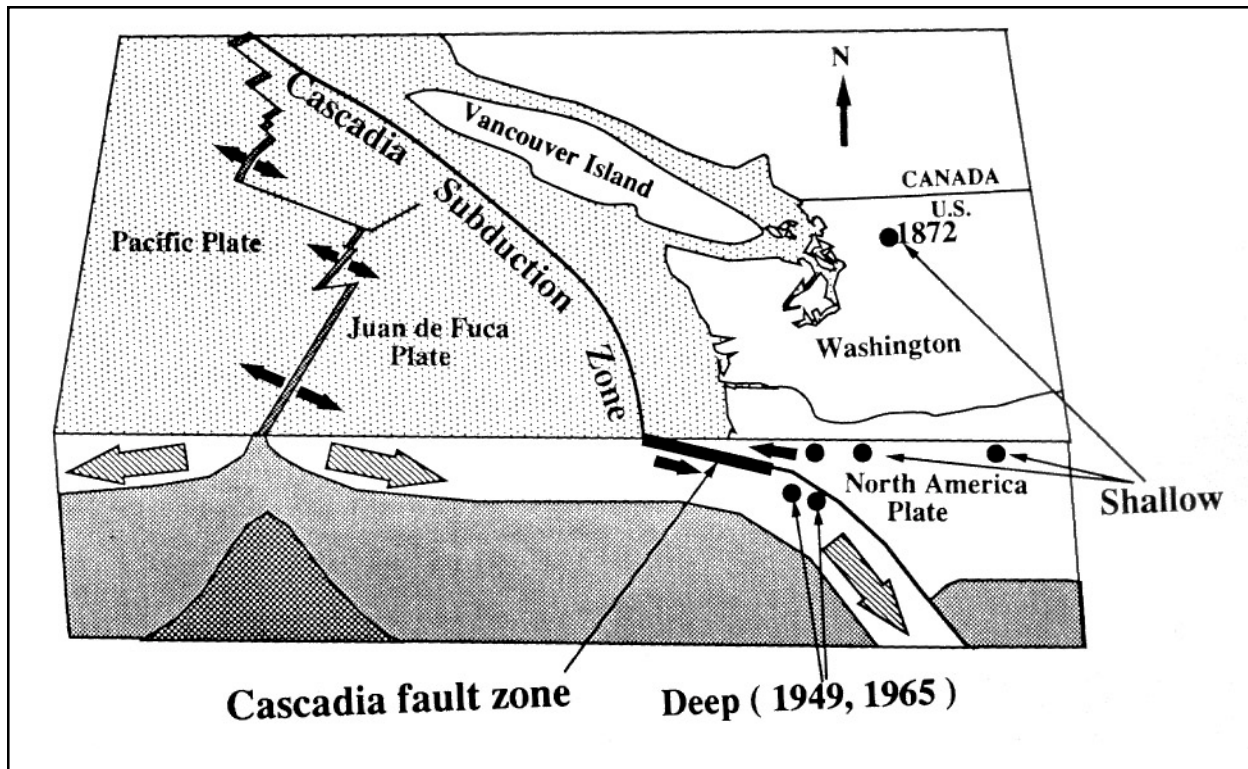
deep, and subduction:

- **Shallow.** Occur in only the North American Plate as it adjusts to the build up of strain along the plate interface. Their depths vary from 0 to 30km. They are usually felt very intensely near their epicenter, but their effects usually diminish quickly with distance. There is a shallow fault system running through the middle of Seattle.
- **Deep.** Occur in the San Juan plate and usually at depths between 35 and 70km. Since they are farther from the surface, they are not felt as intensely, but are felt over a wider area.
- **Subduction.** An "unlocking" of the interface between the San Juan plate and North American plates. They occur along a sloped plain from where the plates meet off the Washington coast to just under the coastal area. This fault is over 1,000 km long. They are the largest type of quake with magnitudes from 8.0 to over 9.0.

There are four ways to measure an earthquake:

- **Richter Scale.** The most common measure mentioned in the media is the Richter scale (abbreviated MI) even though it is rarely used by

Figure 1. Cascadia Subduction Zone



Source: USGS Open-File 94-226B

contemporary seismologists. It is based on the amplitude of ground motion at a seismometer adjusted by the distance to the source. Since the displacement is related to the amount of energy released, it is an attempt to measure of energy released by an earthquake. Other magnitude scales have been developed using different data to achieve faster and/or more accurate measurement of the earthquake's energy. A "moment magnitude measurement" is generally agreed to be the best single measure of size available, but it requires a large amount of data to be determined. Often different techniques will produce slightly different measurements of magnitude which can cause some confusion

- **Modified Mercalli Intensity Scale** (Table 8) is a subjective measurement of earthquake effects. It has twelve steps each of which describes damage to structures. Each step is a stronger intensity. Maps drawn from felt reports are useful in determining areas of damage concentration.
- **Acceleration.** Another common measure, especially in structural engineering, is acceleration. It is the velocity at which a reference point moves during ground motion and is expressed as a fraction of gravity (g): the higher the acceleration the more

stress on a building. Seismic acceleration is divided into horizontal (east-west and north-south) and vertical components. The distinction can be critical as some structures are designed to withstand motion in some directions better than others.

- **Duration.** The time of ground shaking for each shock. It is a strong indicator of potential damage, especially in soft soils.

Besides the power of the earthquake itself, the geology of the area in which it occurs plays a major role in determining the amount of damage. Seismic waves attenuate as they move away from the epicenter, but can change amplitude as they move through different types of soil and rock. Soft soils amplify seismic waves causing more vulnerable soil farther from the epicenter to shake more intensely than less vulnerable soils closer to the epicenter.

Local geology also contributes to secondary incidents such as liquefaction and landslides. Liquefaction is a special type of ground settlement that occurs in soils containing large amounts of suspended water. In an earthquake loose soils compact, displacing and pressurizing the water. The "solid ground" then turns into mud. Whole buildings have overturned when the underlying soils lose enough tensile strength to support

Table 1. Modified Mercalli Intensity Scale .

I.	Not felt except by a very few under especially favorable circumstances.
II.	Felt only by a few persons at rest, especially on upper floors of building. Delicately suspended objects may swing.
III.	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
IV.	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V.	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI.	Felt by all; many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII.	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII.	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, and walls. Heavy furniture overturned.
IX.	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.

the structure. More commonly, only part of a building sinks causing uneven settling. Once liquefaction has occurred, the muddy soil will often flow laterally resulting in severe damage to structures.

Landslides are historical problems in Seattle. They are a common occurrence in earthquakes which trigger them by shaking unstable or steep slopes. Wet conditions would probably make sliding worse since water-logged soils enhance shear stress in slopes, increasing their chance of failure. Landslides are discussed more fully in their own chapter.

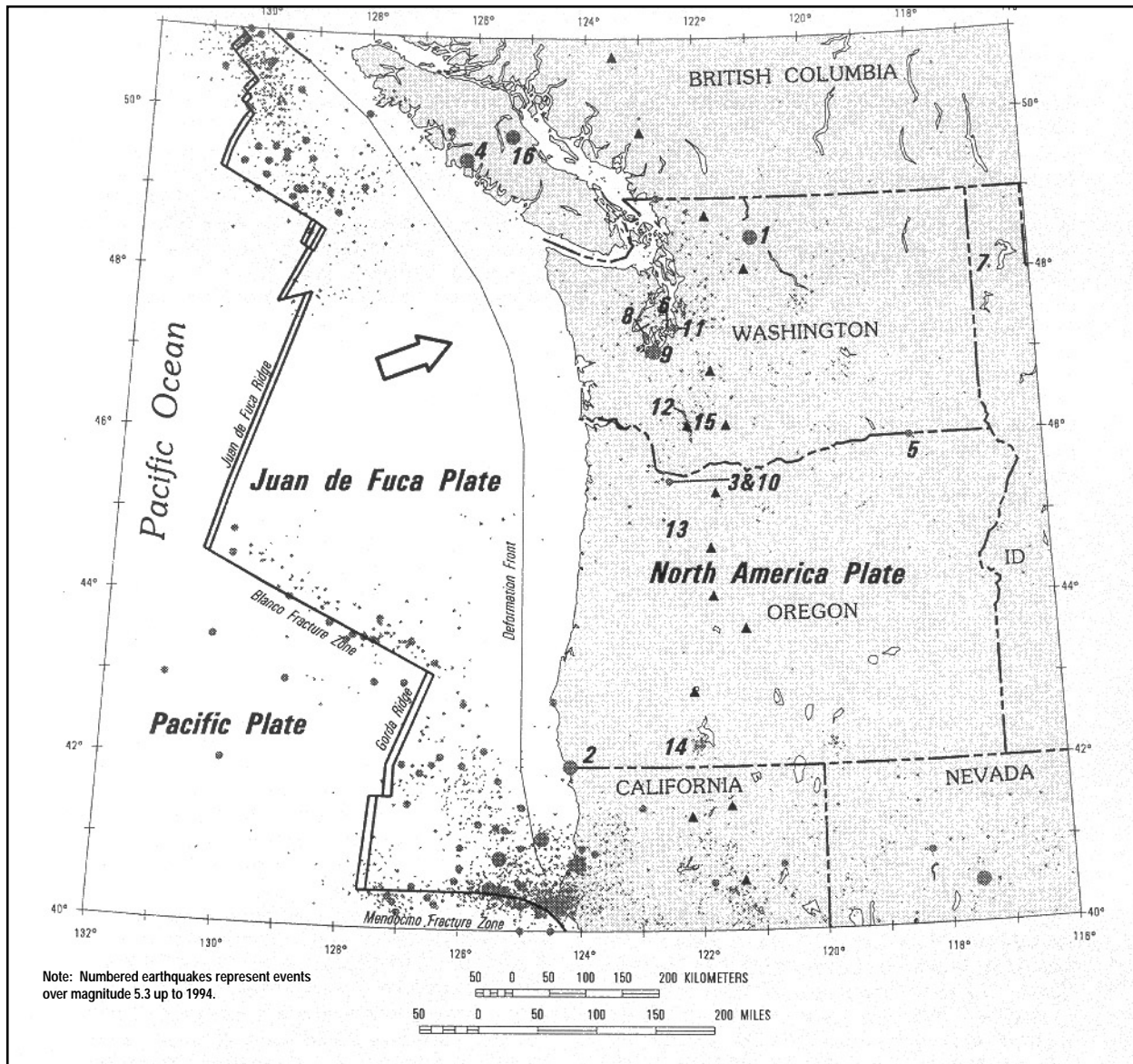
History

The Puget Sound region does not have earthquakes as frequently as Southern California, but when they do happen they can be just as severe. From the time record keeping began, the Puget Sound region has been the most seismically active area in Washington (USGS, 1994). Of those recorded, ten quakes of magnitude 4.9 or greater occurred in western Washington. Eight of them were centered in the Puget Sound region:

Dec. 1872.	Magnitude 7.4 shallow quake shook the North Cascades. It triggered a huge landslide that temporarily blocked the Columbia River.
Jan. 1909.	Magnitude 6.0. centered in the San Juans.

Nov. 1939.	Magnitude 5.75. Centered near Olympia. Chimney and building facade damage near the epicenter. No damage reported in Seattle.
Apr. 1945.	Magnitude 5.5. Centered under North Bend. Chimney and building facade damage near the epicenter. Boy hit by falling brick in Cle Elum. No damage reported in Seattle.
Feb. 1946.	Magnitude 6.3. Centered under mid-Puget Sound. Damage in Seattle mainly limited to the Duwamish Valley and structures built on pilings.
Apr. 1949.	Magnitude 7.1. Centered near Olympia. It had a peak lateral acceleration of .3g and produced VIII MMI damage at its highest intensity. Eight people were killed, mostly from falling brick and the region suffered \$150 million in damages (measured in 1984 dollars). In Seattle, its effects were felt mainly in the northern section of West Seattle and at the mouth of the Duwamish River. (See Figure 3).
Apr. 1965.	Magnitude 6.5. Epicenter closer to the city than the 1949 quake. Its acceleration was lower, .2g. While it did cause type VIII MMI damage, most of its effects were limited to VII MMI. As

Figure 2. Cascadia Subduction Zone Seismicity.



Source: USGS Open-File 94-226B

- in 1949, many ground failures occurred in the Alki and Harbor Island areas, but they were not as concentrated as in the 1949 quake. (See Figure 3). Six people were killed, mostly by falling debris. Damage was \$50 million (1984 dollars). Based on these records, one report estimates that 6.5Mm events have a repeat rate of 35 years and 7.0Mm events have a repeat rate of 110 years (Rasmussen, 1974). However, these rates are highly speculative.
- Jan. 1995. Magnitude 5.0; depth 11 miles. Centered under Robinson Point on Bainbridge Island. No damage reported.
- May 1996. Magnitude 5.3. A shallow quake centered under Duvall. Some light damage reported, mainly objects falling from shelves. No damage reported in Seattle.
- Jun. 1997. Magnitude 4.9. Another shallow quake centered under Bremerton. No damage reported in Seattle.
- There has never been a Seattle Fault or subduction zone quake in modern times, but a subduction quake occurred roughly 300 years ago and there is evidence that the Seattle Fault moved 1,100 years ago. Deposits

Table 2. Summary of Seattle Area Seismicity.

			Rate of Occurrence?		Precursors	
Source Zone	How Big?	Where?	Next Event?	Why do they occur?	Aftershocks	Shaking Effects
Interplate or Benioff Zone	7.1 largest known (1949 Olympia)	At depths of 45-60 km in the Juan de Fuca & Gorda Plates	2 magnitude 7 events in 130 yrs. 5 events > mag. 6 since 1909	Gravitational stress & phase changes within subducting plates.	None expected	15-30 secs strong shaking.
"Deep"	7.5 largest expected		?		None recorded after 1949, 1965. None expected	Accelerations of 0.20-0.35g
Interface of Subduction Zone	1992 Petrolia mag. 7.1 may be on Interface	From offshore deformation front to western Coast Range & Olympic Mts.	Every 300-500 yrs. Last event about 300 yrs ago.	Convergence at locked interface between Juan de Fuca & N American Plates	Probable	Mag. 8, 1-3 min. of strong shaking; accel of 0.5g in urban areas
	8.0-9.0 mag. Expected		?		Many expected mag. To 7.5+	Mag. 9, duration & accel need study
Crustal	1872 N. Cascades largest known, approx mag. 7.5	Known on Vancouver Is., N. Cascades, & Seattle fault	Uncertain, 4 known in last 1000 yrs. From Vancouver Is. To Seattle	Uncertain	Unclear	Accel. > 0.5g but not studied.
(N. American Plate)	Largest expected < mag. 8.0	Other areas are possible - Portland Fault	?		Many expected mag. To 6.5+	Durations not studied, but 20-60 sec likely?

Source: USGS Open-File 94-226B

from massive block landslides into Lake Washington and a tsunami dated at approximately the same time led scientists to conclude they had a common cause, most probable of which is a Seattle Fault earthquake. Since these quakes have happened in the past, they will probably happen again.

Vulnerability

Based on historic seismicity, the most common type of damaging earthquakes are the deep ones. Large events of magnitude of 6.0 or greater are believed to recur every 30 to 50 years. The estimates for large shallow and subduction quakes are less certain. The USGS estimates the subduction events repeat every 200-1,000 years with an average reoccurrence interval of 550 years. At present, estimates of the repeat rates for shallow quakes in the Puget Sound area are tentatively placed at 500 years for magnitude 6.0 events (Shannon and Wilson Fax, 1/21/94).

Table 12 summarizes the characteristics of each of the three types of large earthquakes. The highest estimated magnitude for a deep quake is 7.5, although the most likely event would probably be less intense. They typically last 10-30 seconds, create ground accelerations of 0.20-0.35g, and do not generate any aftershocks. Their epicenters can be anywhere in Puget Sound and would be felt over a large area. The 1949 earthquake was centered around Olympia, but did substantial damage in Seattle.

In contrast, a large subduction zone earthquake would be centered farther away (off the coast) and could be huge. The USGS expects magnitudes of 8.0 to over 9.0. In Seattle it could cause one to three minutes with accelerations of up to 0.5g, and would be accompanied by many aftershocks.

Less is known about shallow crustal earthquakes. A large quake along the Seattle Fault is the worst case earthquake scenario for the city. Magnitudes could reach 8.0 with accelerations of over 0.5g for 20-60 seconds. The epicenter could be directly under the City, making Seattle take the direct brunt of the ground motion.

The most damage-prone parts of the city are where vulnerable geology, structures, and populations coexist in areas that could be easily isolated due to breaks in the transportation network. These locations produce vulnerabilities for the whole city due to their social, political or economic importance.

Seattle's most vulnerable areas geologically are its liquefaction and landslide prone areas which generally

experience more ground motion and higher accelerations than other areas. These areas have been mapped by the City. The major liquefaction zones are in the Duwamish Valley, Interbay, and the Rainier Valley where the land uses are mainly commercial. Landslide areas are spread more evenly throughout the city. The land use in these areas is mostly open space or residential. North Seattle has less slide-prone areas than the central and southern areas. The major northern slide area is Golden Gardens. In the middle of the city, Magnolia, Queen Anne, Madrona, West Seattle, and the northern end of Beacon Hill are all potential slide areas.

Vulnerable structures are also not evenly distributed throughout the city. Those constructed with unreinforced masonry structures (URMs) are the most vulnerable, followed by concrete frame structures with masonry infill and tilt-up structures. Seattle has at least 500 URMs, mainly in the older cores of the city: Downtown, Ballard, Capitol Hill, Columbia City, and the U-District. The number of concrete frame and tilt-up structures is not known, however a 1992 report found them throughout the city, including more recently developed areas like Lake City Way (EQE, 1994). Most of these buildings are commercial and older multi-family dwellings.

Most of Seattle's housing stock would perform relatively well. Although 51% of the housing units were built prior to the introduction of modern seismic codes in 1949, many of them (and nearly all of the single-family units) are wood-frame, a type that performs well in earthquakes from a safety standpoint. Areas with large concentrations of older, multi-family structures may be more vulnerable because taller buildings experience more lateral force during an earthquake and more people occupy them. The older central areas such as Downtown, Belltown, First Hill, Capitol Hill and Queen Anne have the largest number, but significant numbers also exist in the U-District and Ballard.

Linking architecture and socioeconomic factors, the Batelle Institute found a correlation between special needs populations and vulnerable buildings in selected Seattle census tracts using 1980 census data. Many of the areas that contain unreinforced masonry buildings are also home to elderly, non-English speakers, poor and disabled residents, all of whom may need special assistance after a quake. Finding this relationship was an excellent first step towards linking the physical and social aspects of the city and explaining their importance to emergency management. However, there is still much more to understand about how physical damage affects social networks.

Structural vulnerability has an effect on emergency service delivery. Fire stations with their large bay doors are inherently prone to quake damage. A recent survey of sixteen Seattle fire stations found that eleven had a 'high' or 'very high' probability of failure. These are the two highest ratings of the five that the survey gave (EQE, 1994). The East Precinct Police Station is another 'very high' risk. Hospitals were not included in this survey, so the extent of their vulnerability is unknown. All of this information suggests that emergency services would not perform at peak levels after a major earthquake.

One of Seattle's major vulnerabilities is its dependence on its bridges. All the overland routes to and from North and West Seattle go over bridges. In 1992, the city began studying its bridges and found that of the first nineteen surveyed, thirteen had a high probability of catastrophic failure (Seattle Engineering Department, 1992). By the end of 1999 all City owned bridges will have been studied and upgraded. Even with the improvements, these bridges are not designed to withstand a strong Seattle Fault or Subduction Zone quake (shaking over 0.3g for more than a few seconds) nor does the upgrade program cover bridges maintained by the Washington State Department of Transportation which include such critical bridges as the I-5 Ship Canal Bridge and the Aurora Bridge. Furthermore, the Loma Prieta, Northridge, and Kobe quakes showed that even modern freeways and overpasses can collapse. Large parts of I-5 and I-90 rest on columns and run near slopes prone to failure. The Alaska Way Viaduct, which is similar to the one that collapsed in Oakland, is in a liquefaction zone and is considered to be at risk of failure in a major earthquake.

Breaks in the street and bridge network would impair the delivery of emergency services. Most of the city's medical services are on First Hill or Capitol Hill, including Harborview, with the region's largest trauma center. These medical centers would be difficult to reach if a major bridge or section of freeway collapsed. Police and fire stations are more decentralized so the likelihood that at least some units could reach an emergency is better. However, moving police and fire vehicles from a lightly impacted area to a heavily impacted one could be very difficult if bridges fail.

Most earthquakes damage utility networks. Figure 4 shows the location of water pipe breaks during the 1949 and 1965 quakes. Underground systems are the most prone to trouble. The city's water system was evaluated in 1990. Most parts have been given good marks, but there are still sections of the city with brittle cast iron

pipes that will break with even moderate ground motion (Cynga, 1990). Other systems (power, sewer, telephone, and gas) have not been recently studied and their vulnerability must be deduced from past performance and studies of other earthquakes. A Washington State report mentions that both the 1949 and 1965 quakes interrupted service in water, sewer, gas, and electric systems. The report does not describe any damage to the telephone network. A summary of the infrastructure damages from the 1989 Loma Prieta quake outlines the same problems. It adds that widespread utility outages were common, but most were less than a day long (Bolin, 1989). This performance is quite good, but it is important to recognize that the epicenters in these quakes were far from the areas studied.

Secondary impacts from earthquakes have a major bearing on a location's overall vulnerability. The most important are fires, landslides, hazardous materials releases, tsunamis, and seiches.

Fires are the most dangerous of the secondary events. Most of the 28,000 buildings destroyed in San Francisco in 1906 were destroyed in the conflagration that followed the earthquake. Multiple ignitions are the most dangerous post-earthquake fire hazard. The Council on Tall Buildings and Urban Habitat estimates the type of ground motion produced by a moderately large earthquake would produce approximately 5.4 serious ignitions per square kilometer, or about 450 ignitions in an area the size of Seattle (1992). Some of these fires would be in crowded high-rise buildings. Under the same conditions, the Council estimates that each high rise has a 10% chance of ignition. Seattle has approximately 200 firefighters on duty at any given time. Normally, the city would call on neighboring cities for help, but in an earthquake they will probably not be able to provide it. With Seattle's fire-fighting resources spread thin, a conflagration becomes very likely, especially if the water system has been damaged and water pressure drops.

Tsunamis are less possible, but could be highly dangerous. A subduction zone or Seattle Fault quake could generate a tsunami, although only a locally generated tsunami would damage Seattle. Quakes usually have a magnitude of 7.0 or greater before they generate a tsunami (Byrant, 1991; Noson, 1988). They are extremely dangerous since they can occur with little warning, crush buildings, and flood coastal areas. Seattle never considered itself a possible tsunami target, but the discovery of tsunami deposited sand on Bainbridge Island indicates they can happen here. Damage in some areas would have indirect effects on the

rest of the city. They are covered in their own chapter

Landslides and hazardous materials releases are a strong probability in any large earthquake. These hazards are described in their own chapters.

The economic impacts of a large earthquake could be enormous. 75% of Seattle's industry and 18% of its jobs are in liquefaction zones like the Duwamish Valley, Interbay, and the Rainier Valley. Many of the City's most vulnerable structures (Unreinforced Masonry) house commercial uses. Seattle's businesses are vulnerable to disruption in the transportation and telecommunications network. If these systems remain inoperable for a long period of time, Seattle enterprise could face a permanent loss of business as Kobe did following the 1995 earthquake there.

Effects

Any large earthquake could cause hundreds or thousands of deaths depending on the time of day, the day of the week, the weather, and the amount of secondary events. During past quakes, casualties were light, but Seattle could receive a shock much bigger than it has in the past. If this were to happen, there is a likelihood that there could be many more casualties as well. One study estimated that more than 140 buildings are likely to collapse catastrophically, which would produce anywhere from 300 to 1700 dead or seriously injured persons (EQE, 1993). This number does not include those that would be injured by falling debris, landslides, fires, or a tsunami.

Any large earthquake damages the built environment and hampers city service delivery. One of the first post-quake tasks, searching for victims, would be an overwhelming challenge for the city. The same 1993 EQE study estimates that 1,400 search and rescue personnel will be needed to look through the rubble. Seattle does not have this kind of manpower and the amount of outside help from private, state, and federal sources could be stretched thin if other areas are also hard hit. These facts led the study to conclude that the emergency responders would face 'significant shortfalls' in their capacity to respond to post-earthquake demands (EQE, xiii).

Most utility services would be interrupted in large parts of the city. Another deep quake would probably cause only minor interruptions, but they could be severe if the epicenter was closer to Seattle or if the region experiences a large shallow or subduction zone quake that it has in the past. If trunk lines break or critical

substations and transformers are broken, outages would occur over a wide area and if many lines are damaged, outages would persist for a long time.

The number of vulnerable structures indicates that many governmental organizations and businesses would not function normally after an earthquake. Most of these interruptions would not last more than several weeks, but some could last months. In 1965, the Seattle Public School District had to close eight schools while they were inspected. The same quake damaged nearly every waterfront building (Noson, 1988). Several buildings in Pioneer Square had to be taken down. Area businesses suffered millions of dollars in damages. Boeing alone lost \$3,500,000 (1965 dollars) (Seattle Post-Intelligencer, 5/1/65). A Seattle Fault or Subduction Zone quake would magnify these problems.

Transportation problems would be another widely felt inconvenience. If any of the bridges or overpasses go down, the city and state would probably depend on the federal government to help fund the reconstruction. Given the increasingly political nature of this funding, any transportation infrastructure damage could persist for months or even years. Traffic in Seattle is already annoying to many residents and would only get worse with the loss of a bridge or freeway ramp serving thousands of vehicles daily. The loss would shift those vehicles onto other bridges and ramps, increasing congestion.

Total economic losses could range greatly. While the northwest's previous large earthquakes caused less monetary damage than the hundreds of billions lost in Loma Prieta, Northridge, and Kobe, the Puget Sound region is now much larger than it was in 1949 or 1965. It is also important to recognize that Seattle could experience an earthquake stronger than these historic "deep" events.

Conclusions and Recommendations

Earthquakes are both high probability and high impact events in Western Washington, making them the most likely cause of the most damaging disaster Seattle will face. A large earthquake could cause hundreds of deaths and lasting damage the city's economic base. They could spawn hazardous materials spills, landslides, conflagrations, seiches, even a tsunami. Each of these secondary events would cause additional damage and casualties.

The recent discoveries of past subduction and shallow Seattle Fault earthquakes have sparked the City into

action. It has conducted studies of the water system, bridges, and City-owned buildings. It updated its building code in 1992 and increased the role of emergency management. Much of the work has been funded by the National Earthquake Hazard Reduction Program, but it must decide if it will continue research with its own money if this funding is cut. Seismic issues were considered in the Comprehensive Plan EIS. Nevertheless, it has been slow in other areas. The process of identifying vulnerable buildings and mapping them has just begun. Most of this work concentrates on unreinforced masonry structures. Recent findings that tilt-up and some types of reinforced masonry structures are also susceptible to damage, suggest expanding the scope of this work. Without this information development of benefit/cost analysis of mitigation projects like updated critical areas zoning, development review, lution is difficult to achieve. The City government should work to expand its information base and then take a quantitative look at potential solutions.